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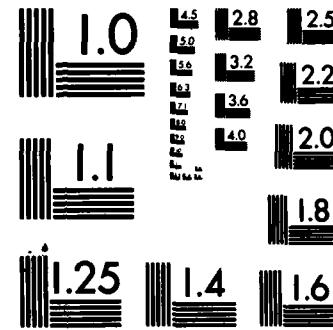
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Collective Ion Acceleration by a Reflexing Electron Beam: Model and Scaling

F. M. MAKO

*Beam Dynamics Group
Plasma Physics Division*

T. TAJIMA

*Institute for Fusion Studies
University of Texas
Austin, Texas 78712*

May 11, 1984



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COLLECTIVE ION ACCELERATION BY A REFLEXING ELECTRON BEAM: MODEL AND SCALING

I. INTRODUCTION

Experiments of collectively accelerating ions utilizing a reflexing intense relativistic electron beam in a plasma have been carried out.^{1,2} These experiments began to reveal several characteristics of the acceleration mechanism albeit by bits and pieces. It is the purpose of this paper to present the latest understanding of the acceleration mechanism by closely comparing the experiment¹, analytical theory and numerical simulation.

One of the first explanations of the mechanism of collective ion acceleration from a reflexing intense relativistic electron beam may be found in Ryutov and Stupakov.³ In their model, an intense electron beam is injected through a thin metal anode into a pre-formed plasma density gradient, see Fig. 1(a). The plasma density abruptly drops to zero in a short distance beyond the anode. A calculation of the potential of a similar situation intended for study of ion collective acceleration was carried out in Ref. 4. This configuration forces the beam to turn around in its own space charge at the position of the virtual cathode [Fig. 1(b)]. With the anode voltage being applied to the returning electrons, the beam is forced into an oscillatory or reflexing state. In this model³ an infinite magnetic field is applied along the direction of beam propagation, thus constraining the model to be one dimensional. The aspect of cylindrical geometry considered in Ref. 4 can be neglected here, since the collisionless skin depth is assumed to be shorter than the cylinder radius. Also, the beam does not have a bulk rotation⁵ but can acquire Larmor rotation. Larmor rotation is provided, in the optimal ion acceleration case, by elastic scattering of the beam as it passes through the anode foil.

Ion acceleration takes place by a mechanism due to the ambipolar field. The ions located at the plasma vacuum boundary are accelerated by the space charge electric field of the reflexing electrons which extend into the vacuum region. Ions are therefore accelerated in the direction of beam propagation. Since the ions move towards the virtual cathode and the virtual cathode cannot move without the ions, it might be expected that the ions and virtual cathode move in a synchronous fashion. Thus, energetic ions would be expected. The ion energy would, of course, be bounded above by the ion to electron mass ratio times the initial electron energy; that is, when the ions reach the initial electron velocity.

Ryutov et al.³ argued that acceleration of ions ceases before ions acquire the electron velocity, which is in qualitative agreement with the experiments.^{1,2} Ryutov's model proposed two factors which limit the ion velocity from becoming equal to the initial electron velocity. The first constraint is imposed by allowing electron scattering with the anode. As the beam passes many times through the anode, the electron parallel energy is converted to perpendicular energy by elastic scattering in the anode. The final parallel electron velocity after scattering is but a small fraction of its initial velocity. Thus, the final ion energy is limited by the final parallel electron velocity. The second constraint is that the diode is "turned off". That is, the cathode is no longer allowed to emit new electrons. This condition is imposed by the space charge of the reflexing beam in the diode region. Hence, without a "fresh" supply of the energetic electrons the final ion velocity is limited to the final parallel electron velocity after scattering. In Ryutov et al.'s model these two elements limit the maximum ion energy. The ratio of energy for an ion with a charge state of unity to the initial electron energy is predicted to be between two and five, depending on whether the beam is non-relativistic or ultra-relativistic, respectively.

It becomes evident, however, from experiments⁶ that the diode is in fact not "turned off", in contradiction to Ryutov's model. In addition, it will be shown below that electron scattering by the anode is not as complete as calculated in Ryutov's model. These observations invalidate Ryutov's model as it is. We have to construct a physical model that is consistent with and constrained by experiment.^{1,6} This method is somewhat phenomenological in a sense that we provide a (nonlinear) relation between the electron density and the potential suitable to and constrained by experiment, replacing Ryutov's invalid relation between the density and the potential based on the above mentioned two factors.

Two objectives of this paper are as follows. The first objective is to establish our model that is experimentally constrained and consistent with our experimental and numerical observations. Our model is constructed in a spirit similar to but different from Ryutov's reflexing beam model. The second is to

examine whether high ion energies are possible by a reflexing electron beam mechanism.

Many quantities can be calculated and compared to experimental values. However, the most important signature of an acceleration mechanism is the ion energy distribution it produces. Comparison of the ion energy distribution forms the basis for establishing the validity of our reflexing beam model. A nonlinear, self-similar model of Ryutov et al.'s type is introduced here to include a measured state of the electron beam. Our modified model or experimentally constrained model is then used to predict the ion energy distribution. Good agreement is found between the measured and the calculated ion distributions and, further, the numerical one. We establish scalability of the reflexing beam model by using a particle code to solve the initial value problem. Simulation shows a similar distribution obtained in the experiment and our theoretical model. It shows that there is a limitation in the ion acceleration process. This limitation seems intrinsic to the present acceleration mechanism in addition to the models self-similarity limitation. The limitation is different from the external limitations considered in the Ryutov model. Synchronization between ion acceleration and the accelerating field is found to be phase unstable. This instability occurs because the virtual cathode is not locally neutralized at a rate sufficient enough for the virtual cathode to keep in step with the accelerated ions. The maximum ion energy is at most several times the electron energy.

In the next section the fluid equations are used to determine the ion response to the electron beam. The steady state electron beam density as a function of electrostatic potential is calculated using experimental constraints. The solution of a final state is found by the self-similarity method. The ion density and velocity are calculated as a function of position and time in the final state. Also, the electrostatic potential and field are calculated. We find the density as a function of potential relation is different from Ryutov's and consequently we show that the maximum ion energy is calculated differently from Ref. 3. Finally, our theoretical ion energy distribution is calculated and compared to experimental and numerical results and is in good agreement.

The third section contains results from the particle code simulation. A one-dimensional space and three-dimensional velocity electrostatic

relativistic particle code is used to evaluate the ion acceleration mechanism. At the initial time step an intense electron beam begins to be injected normally through a grounded metal plane into a dense plasma. The plasma density abruptly drops to zero in a distance large compared to the plasma Debye length and short compared to the distance between ground planes. The above mentioned two factors that determine the maximum ion energy in the Ryutov model are not observed here. Simulation can be done in order to examine the accessibility of the obtained analytical solution and the scalability of the mechanism, not subject to the external limitations discussed above nor the assumption of self-similarity. The ions at the plasma front reach a maximum energy after about ten plasma periods. After this time the ions lose synchronization with the accelerating field and drift past the virtual cathode. The virtual cathode is not neutralized rapidly enough for the accelerating field to keep in phase with the energetic ions. This completes the objective of this section, suggesting that the reflexing beam scheme does not seem a scaleable mechanism for achieving high ion energies.

The final section draws the conclusions.

II. THE REFLEXING BEAM MODEL

In this section we consider the electron beam driven expansion/acceleration of a collisionless plasma. From the reference frame of the ions the beam electrons will appear to be in a steady state since the beam electron plasma period is short in comparison to the time scale for ion motion. The thermal energy of the ions will be neglected since this is small in comparison with the final accelerated ion energy. A one-dimensional treatment is sufficient since the ions are radially confined by the electrostatic field of the electron beam and the electron beam is forced to be one-dimensional by a large external magnetic field. Thus the fluid equations are used to describe the response of the ions to the electrostatic field due to the electron beam

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial z} (v_i n_i) = 0, \quad (1)$$

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial z} = \frac{q}{M} \frac{\partial \phi}{\partial z}, \quad (2)$$

where v_i , n_i are the ion velocity and density, respectively. M and q are the ion mass and charge, respectively. ϕ is the electrostatic potential, z is

the ion axial position coordinate with its origin at the plasma front and t is the time where $t=0$ corresponds to the beginning of the plasma expansion/acceleration. To close Eqs. (1) and (2) it will be necessary to determine the electrostatic potential as a function of electron beam density and assume quasi-neutrality when the ions have evolved to a self-similar state. At this point, if it were assumed that the electron density as a function of potential followed the Boltzman relation, then it would be found that the ion velocity could increase indefinitely given sufficient time. This result has been shown by a self-similar calculation⁷ and also by numerically solving the fluid equations⁸. Since this result is inconsistent with observation and Ryutov's results are not adequate for detailed comparisons, it becomes necessary to formulate an expression for the electron density that can be experimentally constrained.

For a reflexing electron cloud the distribution function will be approximately symmetric in the axial speed, thus the density will be given by,

$$n_e = 2 \int_0^{v_{\max}} g(z, v_z) dv_z, \quad (3)$$

$$\text{where } g = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(z, v_x, v_y, v_z) dv_x dv_y,$$

$$v_{\max} = \left[\frac{2}{m} (E_{\max} + e\phi) \right]^{1/2} \text{ and}$$

E_{\max} is the initial injection energy of the electrons and e , m = electron charge and mass, respectively. The distribution function f is assumed to be independent of time and the x and y positions.

Now defining the forward current density by,

$$J = -e \int_v^{v_{\max}} v_z g dv_z. \quad (4)$$

The lower limit v is varied experimentally to determine $J(z, v)$.

Now differentiating Eq. (4) with respect to v , solving for g and substituting into Eq. (3), then

$$n_e = \frac{2}{e} \int_0^{V_{\max}} \frac{(dJ/dv)}{v} dv . \quad (5)$$

At a given position in the reflexing electron cloud where the potential is ϕ the total particle energy is given by,

$$E = \frac{1}{2} mv^2 - e\phi. \quad (6)$$

Making a change of variables from v to E then Eq. (5) becomes

$$n_e = \frac{(2m)^{1/2}}{e} \int_{-e\phi}^{E_{\max}} (E + e\phi)^{-1/2} \frac{dJ}{dE} dE \quad (7)$$

All that is needed to complete Eq. (7) is a measurement of the current density as a function of energy.

From Ref. 6 the experimentally constrained relation for $J(E)$ is given by

$$J(E) = -J_0 (1 - E/E_{\max})^\alpha, \quad (8)$$

where $J_0 = |J(E=0)|$ and $\alpha = 3.42$. Experimentally Eq. (8) is arrived at by varying the foil thickness which covers a current collecting probe. This probe is located down stream from the acceleration region but faces towards the oncoming oscillating electron cloud. Equation (8) includes the fact that the diode was still "turned on" during the beam pulse length. This condition was mentioned in the introduction as a contradicting factor in Ryutov's model which prevents ions from reaching higher energies.

Now let $X = \left[\frac{E + e\phi}{E_{\max}} \right] a^{-1}$ and

$a = 1 + \frac{e\phi}{E_{\max}}$ then Eq. (7) using Eq. (8) takes the form

$$n_e = \left(\frac{2m}{E_{\max}} \right)^{1/2} \frac{J_0^\alpha}{e} a^{\alpha-1/2} \int_0^1 X^{-1/2} (1-X)^{\alpha-1} dX.$$

The integral is just the Beta Function which when rewritten in terms of the Gamma Function, gives

$$n_e = \left(\frac{2m}{E_{\max}} \right)^{1/2} \frac{J_0^\alpha}{e} \frac{\Gamma(1/2) \Gamma(\alpha)}{\Gamma(\alpha + 1/2)} \left(1 + \frac{e\phi}{E_{\max}} \right)^{\alpha-1/2} .$$

For simplicity α is taken to be 3, finally

$$n_e = n_o (1 + e\phi/E_{\max})^{5/2}, \quad (9)$$

where $n_o = \frac{16 J_o}{5 e} \left(\frac{2m}{E_{\max}} \right)^{1/2}$. Here the non-relativistic energy conservation equation was used for $v(E, \phi)$, since most of the electrons are not relativistic. Equation (9) differs from Ryutov's expression³ which was based on two invalid points, as we discussed earlier: Ryutov et al.'s expression has a power exponent of 1/2 instead of 5/2.

Our next concern is the solution of Eqs. (1) and (2) for ion response to the electron beam. The electron beam density and the electrostatic potential are related through Eq. (9). Since the final state of the ions is what we need for making a comparison with the experimental results, we will then solve Eqs. (1) and (2) in the self-similar state. In the self-similar state the charge density will be quasi-neutral. Hence, the self-similar form of Eqs. (1) and (2) along with Eq. (9) form a closed set of equations. The self-similar condition is invoked by making Eqs. (1), (2) and (9) functions of the self-similar parameter ζ :

$$\zeta = z/(v_o t), \quad (10)$$

where $v_o \equiv \left(\frac{q\phi_o}{M} \right)^{1/2}$ and $e\phi_o = E_{\max}$. With the following definitions

$$U \equiv v_i/v_o,$$

$$N \equiv n_i/n_o, \quad (11)$$

$$\psi \equiv \phi/\phi_o,$$

and Eq. (10), Eqs. (1) and (9) become

$$N'(U-\zeta) + N U' = 0, \quad (12)$$

$$U'(U-\zeta) + \frac{d\psi}{dN} N' = 0, \quad (13)$$

$$N = (1+\psi)^{5/2}, \quad (14)$$

where primes denote derivatives with respect to ζ .

Now Eqs. (12)-(14) can readily be solved, then

$$\begin{aligned} n_i &= n_0 \left\{ \left(\frac{5}{6} \right)^{1/2} \left[1 - \frac{\sqrt{3}}{6} \left(\frac{z}{v_0 t} \right) \right] \right\}^5, \\ v_i &= v_0 \left[\frac{5}{6} \left(\frac{z}{v_0 t} \right) + \frac{1}{\sqrt{3}} \right], \\ \phi &= \phi_0 \left\{ \left(\frac{5}{6} \right)^{1/2} \left[1 - \frac{\sqrt{3}}{6} \left(\frac{z}{v_0 t} \right) \right] \right\}^2 - \phi_0. \end{aligned}$$

The electric field is

$$\epsilon = \frac{\phi_0}{v_0 t} \frac{5}{36} \left(\frac{6}{\sqrt{3}} - \frac{z}{v_0 t} \right),$$

where the conservation of energy was used as a boundary condition, i.e.,

$$U^2/2 + \psi = 0 \text{ at } \zeta = 0.$$

The maximum ion energy can now be obtained by setting $n_i = 0$, i.e.,

$$E_{i\max} = 6q\phi_0 \text{ at } \zeta = \frac{6}{\sqrt{3}}.$$

In the experiment the diode voltage was 0.8MV and the ions were doubly ionized helium⁶ thus the maximum ion energy predicted by theory is

$$E_{i\max} = 9.6 \text{ MeV.}$$

The experimental result⁶ for the maximum helium ion energy was 9.6 MeV and therefore is in good agreement with the theory.

The ion number as a function of energy is calculated to be

$$N_i(E_i) = \frac{n_0 A}{\beta} \left[\left(\frac{6}{5} \right)^{1/2} - \left(E_i / 5q\phi_0 \right)^{1/2} \right]^6, \quad (15)$$

where

$$n_0 A = \frac{16}{5} \frac{J_0 A}{e} \left(\frac{2m}{e\phi_0} \right)^{1/2},$$

$$s \equiv \left(\frac{5}{2} \right)^{1/2} \frac{1}{v_0 t},$$

$$A = \pi r_b^2, r_b = \text{electron beam radius},$$

and

$$v_0 = \left(\frac{q\phi_0}{M} \right)^{1/2}.$$

Equation (15) is our main result. The natural logarithm of Eq. (15) is plotted in Fig. 2 along with the experimental data. The following experimental values were used: $J_0 = 40$ kA, $\phi_0 = 0.8$ MV, $q = 2e$ (doubly ionized helium), $t = 100$ ns and $r_b = 2.5$ cm. The agreement between Eq. (15) and the experiment⁶ is reasonable. The relation in Ref. 3 does not provide such a good fit: it has too weak of a slope.

III. SCALING AND ACCESSIBILITY OF THE MODEL

In the preceding section, the analysis assumed that a self-similar state could be reached. To address the question of whether a self-similar state can be attained, a detailed analysis of the initial value problem is required. This detailed analysis should include a self-consistent treatment of the dynamics of all particle species. The problem must be solved from the origin of time when the beam is first injected into the plasma and must include the effects of a finite geometry. Therefore, a particle code has been selected to study this initial condition problem.

The distance between the beam injection and absorption planes was 15 cm. The initial spatial extent of plasma from the injection plane was 0.5 cm. A beam density of $1.3 \times 10^{10} \text{ cm}^{-3}$ was typically used with a plasma density of $1 \times 10^{12} \text{ cm}^{-3}$. A cyclotron frequency of about three times the plasma frequency was used. The beam electron velocity was $0.67c$ with an electron thermal velocity of $0.1c$. The electron and ion temperature were initially equal and an ion to electron mass ratio was 20 or 40. From simulation we obtained a qualitative agreement with experiment (seen in Fig. 2) and in agreement with Eq. (15). Thus the self-similar solution Eq. (15) seems to be an accessible one in the dynamical sense.

Figure 3(a) shows the beam and plasma electrons in phase space shortly after the beam is injected through the plasma (at $t = 5\omega_{pe}^{-1}$). The beam front is accelerated forward by the space charge behind it and the image charges at the grounded absorption plane (which is located at the far right). Just behind the beam front the electrons are slowed down by both the space charge in front of it and the ions in the plasma (since plasma electrons are expelled into the injection plane). Figure 3(b) is the corresponding ion phase space at a time of $5/\omega_{pe}$ after the beam was injected into the volume. At this time the ions have gained very little momentum. Figure 3(c) is the electric field as a function of position at a time of $5/\omega_{pe}$. The electric field is constant at all points beyond 2 cm from the injection plane, since there is no charge located in that region. By comparing Figs. 3(b) and 3(c), it can be seen that the maximum value of the electric field is in spatial phase with the ion front at this time.

Figure 4(a) shows the electron phase space at $60/\omega_{pe}$. Now the flow of beam particles has fully developed into a space-charge-limited condition. This condition is characterized by the return flow of beam electrons from the plane of minimum energy to the injection plane. The plane of minimum energy being defined where the beam velocity goes to zero. In this case, it is located at about 5.75 cm from the injection plane. The magnitude of current that propagates beyond the plane of minimum energy is found to be approximately the Child-Langmuir current.^{9,10} This result is expected, since a virtual cathode is formed at the plane of minimum energy.

In Fig. 4(b) it is clear that the ions have been accelerated. At this time ($60/\omega_{pe}$) the ions have reached their maximum energy, which is about three times the electron energy. The main point of this section is now established. By comparing the position of the maximum electric field in Fig. 4(c) with the position of the maximum ion momentum, ions are now in a decelerating electric field and thus the ion acceleration process has become phase unstable. For times up to $200/\omega_{pe}$, this phasing condition did not improve, but only oscillated in time.

Several ideas were tried in an attempt to break up this instability, however all ideas that were tried failed to increase the ion energy. First, a

large temperature spread was given to the beam in order to smear the electric field over the ions. The thermal energy was comparable to the depth of the potential wells in the vicinity of the ions. Next the beam density was increased in order to add additional "pressure" to the ions. The increase in beam density was accomplished by re-cycling the beam electrons that returned to the injection plane from the plane of minimum energy. This method of increasing the beam density was also used to represent reflexing of the beam electrons. When the ion mass was doubled, the ion velocity decreased inversely as the square root of the mass. Thus, the acceleration process appears to be momentum limited, since the number of accelerated ions remained constant.

Another thought was that the phase instability was only temporary or periodic in time. However, the simulation was run up to a time of $200/\omega_{pe}$. This only showed that the ion velocity oscillated to a maximum every ion plasma period. This ion velocity oscillation correlated with the position of the peak electric field and the virtual cathode oscillating at the ion plasma period. When the position of the electric field peak or the virtual cathode reached a maximum, the ion velocity reached a minimum value. A virtual anode formed when the ion velocity was a minimum and it disappeared at the ion velocity maximum. The appearance of a virtual anode was observed experimentally by the first author⁶. In another simulation^{11,12} virtual anodes were also observed. However, their ion energy reached a maximum when the virtual anode appeared. In spite of this contradiction in details their ion energy gain was approximately the same. One remaining task to be explored is a scaling of energy with respect to the system length of simulation.

The essential problem with the reflexing beam mechanism is first that the peak electric field forms between the highest electron and ion densities. Secondly, a low density of initially accelerated ions can drift force-free by forming a charge neutral region with the transmitted electron beam. Thus, it appears, within the context of this mechanism, that a phase instability is irrevocable. This further limits the maximum ion energy obtainable based on the self-similarity solution Eq. (15).

IV. CONCLUSIONS

We explored the mechanism of collective ion acceleration done in the experiment^{1,6} and theoretically established the validity of the reflexing beam model. We derived the ion population as a function of energy and compared this expression with experimental and simulation results, a favorable comparison forms the basis for model validity. In addition, the reflexing beam mechanism was found to be unsuitable for scaling to high ion energies, since the accelerating mechanism appears to be phase unstable. The theoretical expression for the energy spectrum of ions Eq. (15) may be useful in other applications as well (such as in astrophysical settings and beam injection experiments).

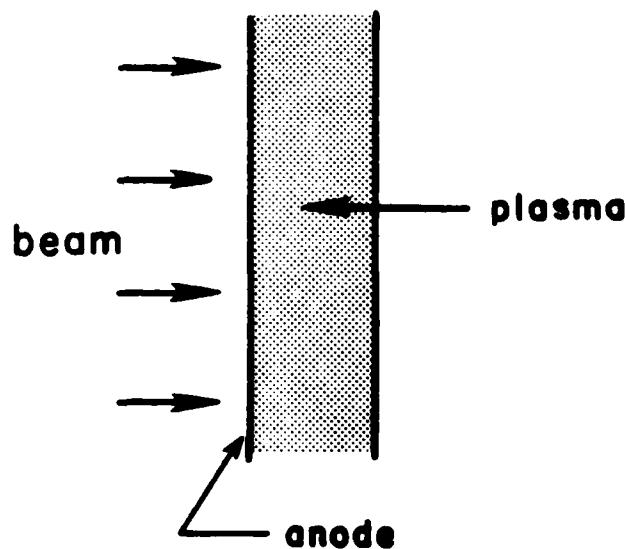
Although it does not seem possible to alter the internal aspects of the acceleration mechanism for removing the instability, it may be possible to circumvent the problem. Since the rate of charge neutralization of the potential well is too slow for the well to keep in phase with the ions, a method of increasing the rate of charge neutralization must be externally invoked. This can be accomplished by adding or creating more plasma at the virtual cathode when the phase instability appears. One way of adding plasma would be from sequentially timed plasma sources, though this approach may turn out to be technically difficult. A continuous version of this idea has been explored by Olson.¹³

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(a) $t=0$. The beam is injected into dense plasma.

$(n_p \gg n_b)$



(b) The beam is space charge limited.

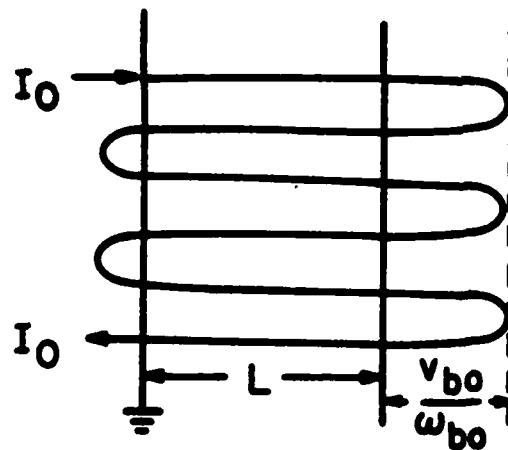


Figure 1

Electron beam injected through an anode into a plasma that extends only a short distance beyond the anode. $B_z = \infty$. In 1b, L is length of the plasma after $t=0$, v_{bo} and ω_{bo} are the electron velocity and beam plasma frequency, respectively. The collisionless skin depth v_{bo}/ω_{bo} is the distance that the beam extends into the vacuum region as measured from the plasma front. I_0 is the injected current. The squiggly line represents electron reflexing.

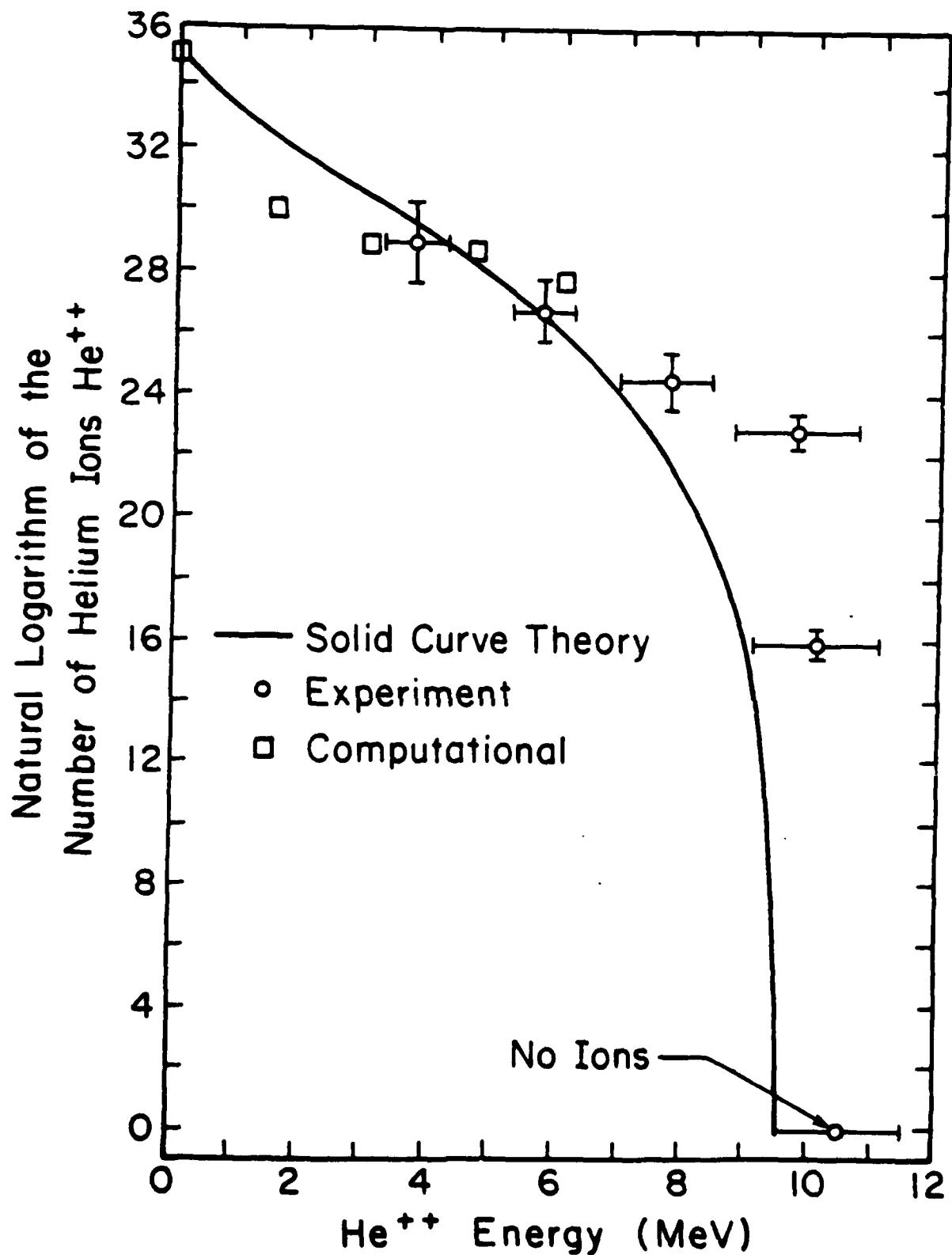


Figure 2
 Comparison between theory, experiment and simulation, of the natural logarithm of the ion number vs. energy.

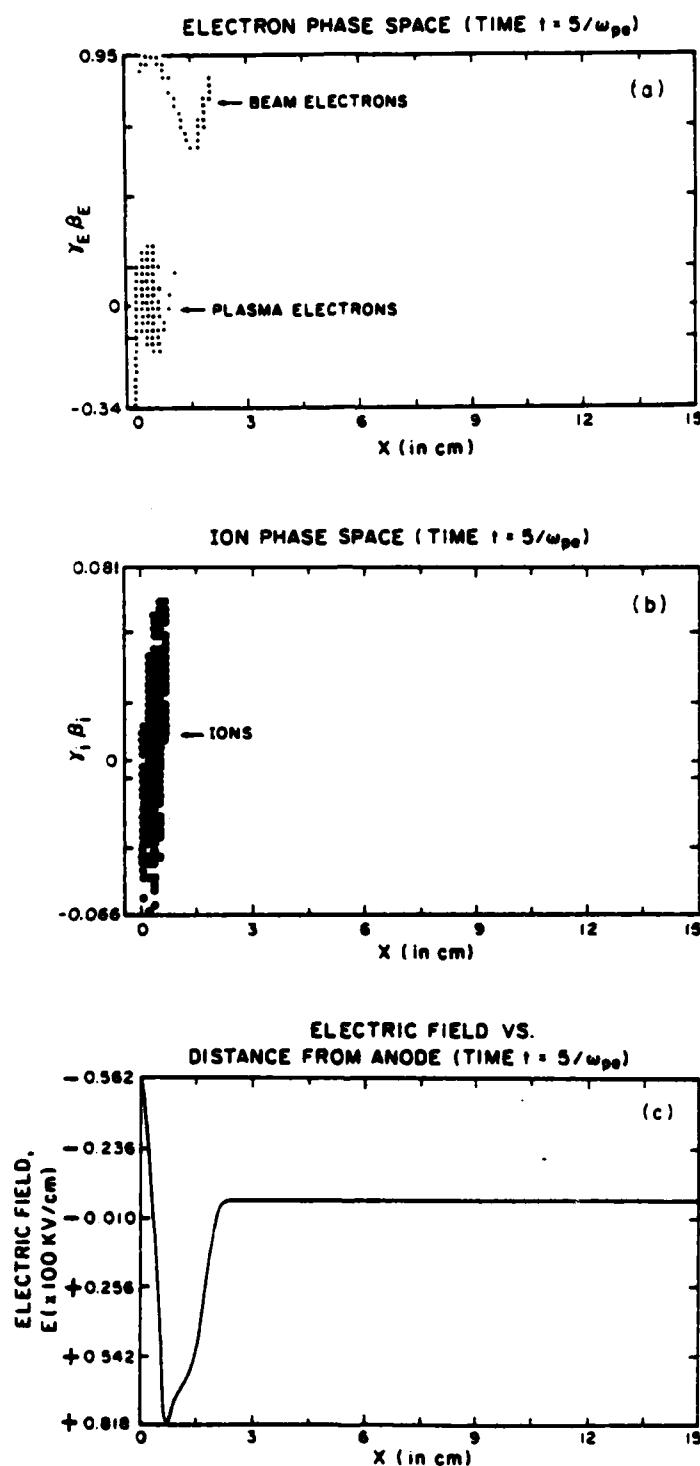


Figure 3

Simulation phase space at early time $t = 5/\omega_{pe}$.

- (a) Electron Phase Space (Beam and Plasma).
- (b) Ion Phase Space.
- (c) Electric Field vs. Position.

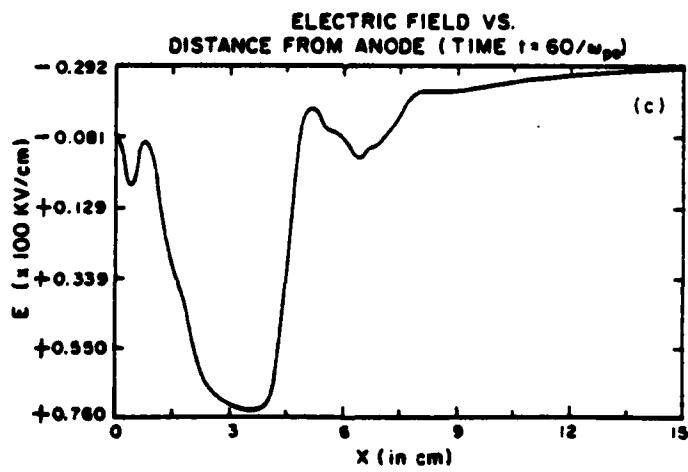
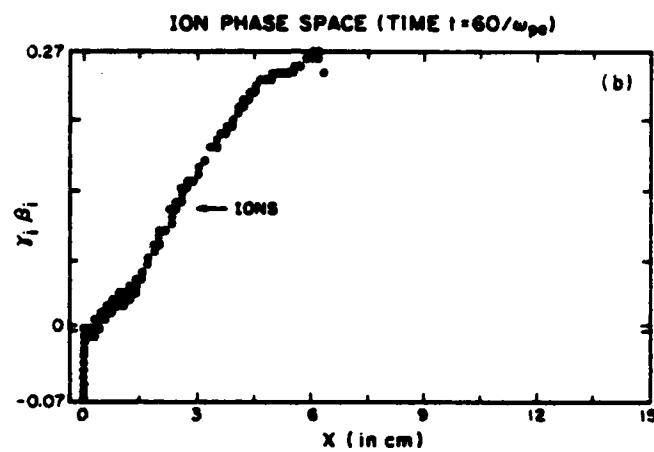
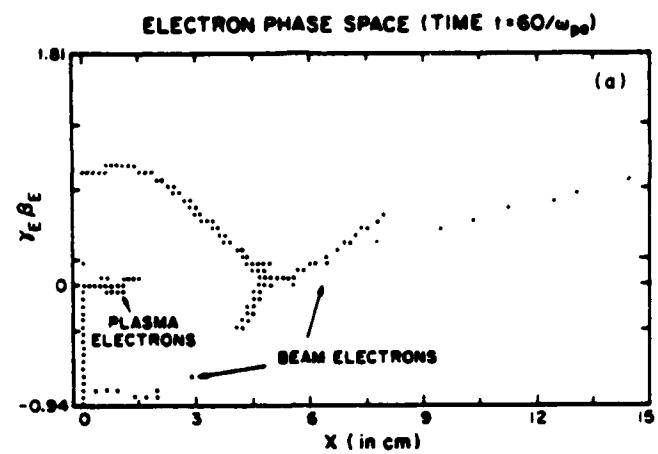


Figure 4

Phase space from simulation in later time $t = 60/\omega_{pe}$.

- (a) Electron Phase Space.
- (b) Ion Phase Space.
- (c) Electron Field.

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